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REVIEW OF THE MAGNETIC FUSION PROGRAM

BY THE 1986 ERAB FUSION PANEL^{*†}

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* Presented to the Magnetic Fusion Advisory Committee (La Jolla, California, December 4, 1986).

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ABSTRACT

The 1986 ERAB Fusion Panel finds that fusion energy continues to be an attractive energy source with great potential for the future, and that the magnetic fusion program continues to make substantial technical progress. In addition, fusion research advances plasma physics, a sophisticated and useful branch of applied science, as well as technologies important to industry and defense. These factors fully justify the substantial expenditures by the Department of Energy in fusion R&D. The Panel endorses the overall program direction, strategy, and plans, and recognizes the importance and timeliness of proceeding with a burning plasma experiment, such as the proposed Compact Ignition Tokamak (CIT) experiment.

1. INTRODUCTION

This presentation is based on the Report of the 1986 Technical Panel on Magnetic Fusion of the Energy Research Advisory Board (ERAB).¹ The U.S. Department of Energy is required to carry out such a review of the fusion program every three years and report its findings and recommendations to Congress. The membership of the 1986 ERAB Fusion Panel is shown in Table 1. Several members of the Panel have extensive experience in areas related to energy research and development.

I begin with the Executive Summary of the Panel's findings, conclusions and recommendations.¹ The Executive Summary is followed by a description of national energy circumstances and policy, fusion program status, role of the Compact Ignition Tokamak (CIT), role of international collaboration, etc., which led to the Panel's findings and recommendations.

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2. EXECUTIVE SUMMARY

a. Panel Findings

1. *Magnetic fusion energy continues to be a uniquely attractive potential power source for the future.*
2. *Throughout the program, considerable progress has been achieved since 1983. This has culminated in the recent advances on the TFTR tokamak at Princeton. Important progress has also been made in Europe with JET and in Japan with JT-60. In addition, significant progress has been made in several alternate confinement concepts under active investigation in the U.S. program as well as abroad.*
3. *The Office of Fusion Energy has dealt effectively with budget reductions, making difficult decisions. Three successive years of budget reductions have curtailed and eliminated some program elements and postponed others. Deferring MFTF-B (the large tandem mirror facility at Livermore) was a difficult, though necessary decision.*
4. *The disaster at Chernobyl and the domestic controversy concerning fission waste storage have resulted in renewed concern about the environment. There are also long term concerns about the use of fossil fuels due to the buildup of carbon dioxide in the atmosphere.*
5. *International collaboration in fusion research is being addressed at many levels of government and plays an important role in both the technical and financial aspects of the program.*

b. Panel Conclusions

1. *Because of the uncertainty of energy supply early in the next century, there is an advantage in testing the feasibility of fusion sooner rather than later. This requires studying the physics of an ignited plasma.*
2. *An ignited plasma experiment, such as the Compact Ignition Tokamak (CIT), is an essential and timely project. It will enhance the likelihood of success with a future Engineering Test Reactor (ETR)*

whether or not the ETR is a multilateral or domestic project. An ignited plasma experiment will require incremental funding above the FY87 level.

3. Further budget reductions, beyond the three years cited above, will jeopardize the overall technical integrity of the program, and will make the U.S. fusion program a substantially less-desirable partner for international collaboration.
4. A good start has been made toward international collaboration, but collaboration on a large device, such as an ETR, is a complicated process that will take time and substantial negotiating effort. The potential savings due to collaboration are considerable and will occur later.
5. Today's environmental concerns about fission and fossil energy cannot yet be extrapolated into the future, but these trends are likely to continue and could be of significant importance to the role of fusion. Furthermore, environmental impact and public safety questions must be addressed during the development of fusion energy.
6. Fusion R&D advances plasma physics, a sophisticated and useful branch of applied science, as well as technologies important to industry and defense. This contribution to a strong national science and technology base warrants a substantial level of investment in its own right.

c. Panel Recommendations

1. Proceed expeditiously with an ignited plasma experiment, such as the CIT, using existing facilities to the greatest extent possible to minimize the additional funding that will be necessary. Early completion of this project will help to determine whether there are unanticipated phenomena associated with a burning plasma that would alter the prospects for proceeding with fusion development. Incremental funds will be needed in order to proceed with the CIT in a timely fashion and to maintain the strength of the base program.
2. While the tokamak configuration is the mainline of present national and international experimental efforts, exploration of selected non-tokamak

concepts as well as tokamak improvements should be pursued. The budget reductions have already resulted in a substantial narrowing of effort. Further reductions would endanger key areas of the program.

3. Continue to study urgently the question of possible atmospheric changes from continued massive use of fossil fuels. The Panel notes that DOE is the lead agency in a multiagency effort to determine the consequences of the buildup of CO_2 . Fusion, second generation fission, and solar technologies are the primary energy options for the future if the atmospheric CO_2 trend is determined to be harmful to the environment. This is a global problem with very significant economic and political consequences.
4. Proceed with the required negotiations to establish major international collaboration in fusion R&D. This should be done recognizing that it will take time and that considerations external to the U.S. program may make it necessary to proceed independently. Reviews of the NRC report of 1984, "Cooperation and Competition on the Path to Fusion Energy," and the ERAB report of 1985, "International Collaboration in the U.S. Department of Energy's Research and Development Programs" indicate that the conclusions of those reports appear to be valid today.
5. The Panel believes that fusion R&D deserves a priority greater than that provided at present by the U.S. government. We recommend that the Secretary of Energy press vigorously for a higher national priority within the Administration.

A summary of changes since the 1983 review, and a description of current national energy circumstances and policy, fusion program status, role of the Compact Ignition Tokamak, role of international collaboration, etc., are now presented. These form the background and rationale for the Panel's findings and recommendations.

3. CHANGES SINCE THE 1983 REVIEW

Since the 1983 ERAB review of the fusion program, a number of changes have occurred in the U.S. program, in foreign programs, and in the world external to fusion research and development. The recent achievements on the Tokamak Fusion Test Reactor (TFTR) at Princeton have shown continued

progress to near-breakeven levels of operating conditions. At the same time, pressures from the federal budget deficit have resulted in three years of declining funding for the magnetic fusion program (38% reduction in real terms). This has resulted in several difficult program adjustments.

The European program has progressed well, both on the Joint European Torus (JET) and in the strong national programs. The Japanese program has brought the JT-60 tokamak into operation. Both the European and Japanese programs appear to have planning and funding stability, and in 1986 each program matches or exceeds the United States' level of effort. Finally, both the European and Japanese programs include planning and analysis leading to the next generation of advanced facilities.

In the world external to magnetic fusion, three significant changes have occurred. Public acceptance of fission-generated power, especially in the United States and Europe, has been dramatically weakened by the accident at Chernobyl. The collapse of the world price for crude oil has brought exploration for oil and gas to a minimal pace, has discouraged conservation, and has started a trend for the United States to increase again its dependence on Mid-East oil. The third factor has been the exploration of joint undertakings, such as international collaboration the next major fusion facility, known as the Engineering Test Reactor (ETR).

Needless to say, all of these changes have had an impact on the report¹ of the 1986 ERAB Fusion Panel.

4. NATIONAL ENERGY CIRCUMSTANCES AND POLICY

No factor is more intimately involved in future economic health--domestically and globally--than an adequate, acceptable supply of energy. Furthermore, an increased demand for energy has a greater potential for producing undesirable long-term effects on the climate than any other trend. At present, the U.S. has achieved its energy goal of "an adequate supply of energy available at a reasonable cost." Furthermore, it is likely that the U.S. will continue over the mid-term to enjoy energy stability, energy security and energy strength through its reliance on coal, nuclear, renewable and conservation technologies.

However, the future energy supply early in the next century is unclear. It is generally agreed that in time there will be a pronounced shift in production towards the Middle East, which has over half of all proven reserves and one-fourth of the undiscovered resources. This could again make this nation vulnerable to foreign supply. As for coal, the most abundant U.S. energy resource, it has been speculated that there may be a limit to its usage on a global basis due to atmospheric pollution. Also, the recent accident at Chernobyl and the domestic controversy concerning fission waste storage have generated concern about nuclear energy's effects on the environment.

It is no longer adequate that a particular energy technology provide low-cost energy. Today's energy technologies must not only provide energy at a reasonable price, they must do so in an environmentally acceptable manner and not endanger public health and safety. Furthermore, the assurance of an adequate and secure source of supply is a necessary prerequisite for the introduction of a new energy technology.

It is in this context that the 1986 ERAB Fusion Panel reaffirms the unique attractiveness of fusion as a future means of generating power. Fusion has a virtually inexhaustible fuel supply. It appears to avoid the long term storage of high-level, long-lived radioactive wastes characteristic of the fission process. Fusion has the potential of reducing the dependence on fossil fuels that may present a major threat of atmospheric pollution. This is particularly important if the industrialization and continued urbanization of the third world is realized. Using fusion for power generation would also permit reserving oil for transportation and industrial uses. With the nature of the fusion process and the experience already acquired in fission power generation, it should be possible to design and construct generating stations that are safe, benign, and acceptable to the general public.

The above points are not new. However, they deserve additional emphasis in view of the convincing technical progress within the fusion program and in view of the shock to the public perception of nuclear power by the Chernobyl accident. The Panel reaffirms the potential merit of fusion power recognizing that actual deployment lies well into the future.

In addition to the long-term energy objective of fusion research, there are also near term benefits. Meeting the technological requirements of fusion has led to advances in fields ranging from microwave technology, to materials science, to applied superconductivity. In addition, plasma physics, the major academic discipline of fusion, has developed over the last twenty-five years into a sophisticated and useful branch of applied science. The major areas of application of plasma physics have been, besides fusion, the understanding of the Earth's magnetosphere, interstellar space, and astrophysical plasmas; and the advancement of various high technologies, such as x-ray and ultraviolet light sources, free electron lasers, intense charged particle beams, gyrotrons, and so forth. Plasma processing, which is used in semiconductor manufacturing, machine tool hardening and other industrial areas, is also a promising application of plasma physics. Furthermore, the fusion program has consistently trained large numbers of high-caliber scientists and engineers. Many enter other areas of research and make major contributions to defense applications, space and astrophysical plasma physics, materials science, applied mathematics, computer science, and other fields. Benefits such as these constitute an important contribution to the national science and technology base.

To summarize, despite all the changes in the national view of energy, the inherent attractiveness of fusion has not diminished since the inception of the program. Moreover, the future promise of safe and inexhaustible energy continues to be the primary motivation for the program and justifies its continuation at present or increased levels of support. The near term benefits of fusion R&D are also significant and warrant substantial support in their own right.

5. PROGRAM STATUS

a. Technical Status: Since the 1983 ERAB review there have been significant technical advances in the U.S. fusion program. These are well known to the Magnetic Fusion Advisory Committee and are enumerated in the ERAB Panel Report.¹ Therefore, the details will not be presented here. (See Appendix A.) The culmination and most visible signs of this progress are the recent results on TFTR. However, in view of budget cuts over the past three years, it is the view of the ERAB Fusion Panel that the United

States is beginning to lose its competitive edge over the European and Japanese programs.

b. Program Changes: The fusion budget has experienced significant cuts for three years in a row. The budget has been reduced from \$468 million in 1984 to \$346 million in 1987, corresponding to a 38% reduction in constant dollars. While the program has coped effectively with the reductions, the Panel believes that further reductions will jeopardize the overall strength and technical integrity of the program.

The program has adjusted to the budget reductions in several ways. First, the program has identified the Compact Ignition Tokamak (CIT) as a cost-effective next step to investigate ignition physics issues. Second, the program has embarked aggressively on international collaboration. The third measure taken by the program has been to formulate and implement a new plan, called the Magnetic Fusion Program Plan (MFPP).² Fourth, the program has reduced significantly many areas of research.

As a result of the budget reductions, the program has been significantly narrowed, and all parts of the program have been affected. In the confinement systems area, the mirror program has been reduced from a main-line to an alternate concept, and the operation of the MFTF-B tandem mirror has been deferred. In addition, preparation for tritium operation of TFTR has been delayed, and a number of tokamak improvement experiments were not funded. In the alternate concepts area, initiation of the next step experiment in the reversed-field-pinch program was delayed. In technology areas, research on longer-term technologies, such as negative ion neutral beams, has been deferred. Likewise, university experiments, both small- and medium-scale, have been canceled or deferred. As a final point, major participation by United States' industry in the fusion program has been reduced dramatically.

While the Panel believes that much credit must be given to DOE for making difficult decisions within stringent budget directives, the Panel is very concerned that the U.S. program will lose both momentum and technical integrity if there are further budget reductions. Therefore, the Panel recommends that incremental funding be provided for CIT, a program initiative it strongly endorses. (This point will be discussed later.) There is also a strong concern that upgrading existing devices and exploring

promising alternative confinement concepts should not be further constrained at this time. Finally, maintaining a strong United States' program will increase the likelihood of establishing a mutually acceptable international collaboration.

c. Program Strategy: As stated in the Magnetic Fusion Program Plan (MFPP),² the goal of the program is to provide on roughly a twenty-year time scale, the scientific and technological base for an assessment of magnetic fusion. The program plan defines four key technical issues which must be resolved to meet the program's goal. These are:

1. Magnetic Confinement Systems
2. Properties of Burning Plasmas
3. Fusion Nuclear Technologies
4. Fusion Materials

The present program strategy has two parts. First, it relies primarily on the U.S. program to provide facilities that address key technical issues on an individual basis. Second, it relies on international collaboration to provide the large facilities needed for integrated tests, such as the Engineering Test Reactor.

In addition, the program is carrying out a detailed planning effort, known as the Technical Planning Activity (TPA),³ which involves a broad participation by the fusion community. The ERAB Fusion Panel believes that the TPA has made significant progress. Its accomplishments include: detailed definitions of the technical issues; definitions of the related program areas and elements; statements of research and development objectives; identification of key decision points and milestones; and descriptions of the facility requirements. This work could provide the basis for international collaboration and may be a lasting contribution to planning the world fusion effort.

Overall, the Panel believes that the fusion program is doing a commendable job in the planning area. It has developed a workable strategy that is compatible with the stringent budget situation. It is earnestly pursuing a strategy of international collaboration, and it has defined the detailed technical planning elements that are the basis for a thorough plan.

6. ROLE OF THE COMPACT IGNITION TOKAMAK (CIT)

Since the 1983 review, the fusion program, with broad input from the fusion community, has identified the Compact Ignition Tokamak as the most cost-effective means for resolving the technical issues of an ignited tokamak plasma. The CIT incorporates several features of the LITE and Ignitor designs, and has an estimated capital cost of \$300 M plus about \$60 M for diagnostics and R&D. Furthermore, there are significant site credits which are comparable to the capital cost, particularly if the CIT were sited at the Princeton Plasma Physics Laboratory (PPPL). The CIT would provide the first D-T ignition physics test including studies of confinement and control of a burning tokamak plasma. This would be a significant scientific achievement. In addition, the CIT would provide valuable technical information and experience for operating and optimizing the performance of a multibillion-dollar Engineering Test Reactor.

In addition to being an essential technical next step for the United States' fusion program, there are other important implications of having a burning plasma experiment. First, it would put the United States in a strong position for future international collaboration. Second, it would reinvigorate the United States fusion program which has been losing both personnel and momentum. Consequently, the Panel believes that a burning plasma experiment such as the CIT concept, is essential and timely from both a technical and programmatic point of view.

The Panel believes that an investment in the CIT of \$360 M (including diagnostics and R&D), obtained by making maximum use of the substantial existing facilities, is an exceedingly attractive and effective step that should be initiated as soon as possible.

With regard to funding, the Panel strongly recommends that a budget increase be provided for the CIT. The budget for fusion has been cut three years in a row and the overall program has been narrowed sufficiently. The base fusion program has played a critical role in testing ideas, discovering new effects, and developing the understanding that has led to the successes on TFTR. Further cuts to the base program would jeopardize its technical integrity. It may not be necessary for all of the funds for the burning plasma experiment to be incremental, but some additional funds will

be required so that a burning plasma experiment may proceed in a timely fashion consistent with maintaining a strong base program. The Panel recognizes that this requires a bold initiative in the current budget climate. The Panel believes it will be necessary for DOE to examine program schedules, including the TFTR schedule, to see whether it is practical to defer or rescope presently planned activities to ameliorate the funding impact of CIT.

7. ROLE OF INTERNATIONAL COLLABORATION

Since the 1983 ERAB review, the magnetic fusion program has expanded significantly its use of international collaboration, and the Panel believes that the program should expand it further, aiming towards an international ETR. The current role of international collaboration spans a broad range of activities covering all of the key technical issues identified earlier. Furthermore, it appears that the Technical Planning Activity could play an international role in forming the basis for joint planning in the world fusion community. The Panel believes that international relations in the fusion field should be expanded by continuing to pursue a deliberate policy to achieve this objective. Major international collaboration on fusion development will mean that development can occur in a timely fashion. If each of the world's four principal centers of fusion expertise work separately, development may never occur for some centers and certainly will take long for all. In addition, other benefits should be obtainable. These include sharing the costs as well as the risks of large projects and even helping to build scientific and technical bridges of cooperation in the world.

There are many factors working against international collaboration. These include: national pride; perception of the reliability of partners; transfer of vital technologies; cultural differences--the list is long. Nevertheless, the Panel urges patience and persistence in working toward acceptable working relationships. The Panel also believes that there may be some undue optimism concerning how long negotiations will take and how much money will be saved. The larger the commitment, such as an ETR, or other major program elements, the longer the negotiations will take. In addition, management of a multilateral program will require a more stable,

enduring commitment than is customary in domestic experience. The reward could be earlier accomplishment of the goal of fusion-generated power. Moreover, the experiences at CERN and JET suggest that international collaboration produces far more secondary advantages than can be seen in advance. Finally, some realistic consideration must be given to the possibility that international collaboration on a large scale may not come about.

8. ROLE OF UNIVERSITIES AND INDUSTRY

a. Universities: Although representing a relatively small fraction of the national effort (approximately 10 percent), the universities continue to play a very significant role in magnetic fusion research. Historically, the universities have contributed to the national fusion program in several unique and important ways. These include: (a) educating and training professional researchers; (b) providing the fusion program with a breadth of talent and intellect in the sciences and engineering; and (c) a major source of innovative ideas and scientific and technological advances. With the decrease in the fusion budget, the university activities have also been reduced, but the percentage of the total budget remains approximately the same. Since 1983, however, the number of universities involved in fusion research has dropped from 39 to 32.

Fusion R&D advances plasma physics, which has valuable applications outside of fusion. The fusion program, through the universities, has been the major supplier of plasma physicists for the nation. In fact, national programs such as fusion link universities, industry and national laboratories in a way that facilitates the transfer of ideas, knowledge and technology. With the reductions in the fusion program, the development of new advances based on plasma physics will be adversely affected and the supply of highly trained personnel reduced. It is the Panel's assessment that a continued strong component of university involvement is essential to a vigorous fusion research and development program for the foreseeable future.

b. Industry: The step from feasibility to demonstration of a practical power-generating system is a very large one and its date of accomplishment can only be approximately estimated. However, the practical

application of fusion holds within it the potential for new industrial ventures and international competition for that business. As it stands today, the Japanese fusion program is providing the most thorough and significant industrial involvement. The European program ranks second, with the United States program being the least successful in engaging industry and keeping it involved. With greater industrial involvement in the future, United States' industry eventually would be in a better competitive position and would be more likely to spend discretionary research funds to support DOE efforts. It would also be more likely to invest in university research in support of the fusion program. Furthermore, if industry is visibly active in fusion R&D, more students will be attracted to the university programs.

It is not premature to be concerned now about our competitive position in the international markets of the future. Moreover, the current trend in the globalization of industry and markets suggests that the real competition may already have started and that the penalty for failing to grasp the opportunity to be a competitor is to become the buyer or license holder of foreign high technology in the future.

9. FUSION IS AT THE CUTTING EDGE OF APPLIED RESEARCH

While scientists and engineers have somewhat different views of the fusion program, it is quite clear that its physics is sophisticated and challenging, and several important technologies have been advanced. Plasma physics is relevant to many high technology endeavors in civilian as well as defense programs. The university involvement in the fusion program is both desirable and beneficial to the nation. Advancing scientific knowledge and education has been identified by the full ERAB as a proper objective of DOE civilian R&D programs. In this regard, the fusion program has contributed much to the strength and utility of plasma physics today. Consequently, this aspect of the fusion program warrants substantial support by the federal government in its own right.

REFERENCES

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3. *Technical Planning Activity Final Report*, Argonne National Laboratory ANL/FPP-87-1 (January, 1987).

PANEL MEMBERS

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Table. 1. 1986 ERAB Fusion Panel

APPENDIX A
TECHNICAL ACCOMPLISHMENTS SINCE THE 1983 REVIEW*

Prepared by
 1986 ERAB Fusion Panel

Three years ago, world fusion research still fell short of the minimum reactor goals by roughly a factor of 2 in temperature and a factor of 3 in the quality of energy confinement (as measured by the Lawson parameter $n_0\tau_E$). Present-day toroidal confinement experiments have very nearly succeeded in reaching these goals--and other key reactor requirements as well.

The U.S. tokamak program has led these advances in several important scientific and technological areas, including the achievement of high plasma temperatures ($T_i \sim 20$ keV), confinement quality ($n_0\tau_E \sim 10^{14}$ cm⁻³-sec), and plasma beta ($\sim 5\%$). In 1987, the Tokamak Fusion Test Reactor (TFTR) is expected to achieve breakeven-equivalent conditions in deuterium plasmas. That is, the fusion power which would be produced with a deuterium-tritium fuel mixture will approximate the power required to maintain the plasma temperature.

Alongside these significant advances in experimental fusion parameters, there has been an impressive development of innovative ideas and techniques. The conventional toroidal reactor concept is being extended towards smaller size and higher power density. Encouraging results have been achieved on alternate approaches such as the reversed field pinch, and compact toroids. Also, the tandem mirror approach has provided a promising alternative to toroidal reactor geometry, by sealing up the ends of the "magnetic bottle" with a system of electrostatic potentials.

We summarize here selected significant accomplishments in the U.S. fusion program since the 1983 review.

a. Tokamak Systems

In the TFTR tokamak, well-confined plasmas at ion temperatures $T_i \sim 20$ keV and electron temperatures $T_e \sim 7$ keV have been achieved, approaching the temperatures needed for fusion. These temperatures were achieved

* Excerpts from the 1986 ERAB Fusion Panel Report.

during neutral beam heating at values of the Lawson parameter $n_0 \tau_E \sim 10^{13} \text{ cm}^{-3}\text{-sec}$, corresponding to entry into the breakeven regime.

In the TFTR tokamak, energy confinement has been demonstrated for a dense plasma (at a lower, but significant temperature) for values of the Lawson parameter in the range $n_0 \tau_E \sim 1.5 \times 10^{14} \text{ cm}^{-3}\text{-sec}$. This value is a factor of two larger than that achieved in Alcator C in 1983, and approaches the quality of confinement needed in a full-scale fusion reactor.

Beta values (ratio of plasma pressure to magnetic pressure) of 5% have been achieved in the Doublet III and PBX tokamaks, which are within a factor of two of the requirements for an economic fusion reactor.

Also in the tokamak, empirical energy confinement scalings have been identified which are favorable for reactor sizing. According to one empirical scaling (known as "neo-Alcator" scaling), which fits the data from ohmically heated tokamaks over a wide range of parameters, the confinement time varies with the cube of the plasma linear dimension, as would be expected for a diffusive process in which the transport coefficient depends on gradient-induced "anomalous" processes.

In accordance with theoretical prescriptions, radio frequency waves have been used to drive plasma currents in the Alcator C and PLT tokamaks, thereby permitting confining magnetic fields to be steady-state, a property of importance to the practicality of tokamak reactors. Experiments on radio frequency current drive have exhibited a hot-electron population of current carriers in agreement with theory, and have verified the predicted dependence of current-drive efficiency on plasma density. Using lower hybrid waves, toroidal currents of 500 kA have been sustained on PLT at densities of $1.5 \times 10^{13} \text{ cm}^{-3}$, and currents of 230 kA have been sustained on Alcator C at densities of $5 \times 10^{13} \text{ cm}^{-3}$.

High-power neutral beam and rf sources have been developed that can heat plasmas to fusion temperatures. Neutral-beam heating experiments have verified that the beam ions deposit their energy in the plasma by means of well-understood classical processes. Effective plasma heating by radio frequency waves in the ion cyclotron range of frequencies (ICRF) has been demonstrated on the PLT tokamak at densities of $4 \times 10^{13} \text{ cm}^{-3}$, resulting in

ion temperature increases of 5 keV with 4.5 MW of injected power. Lower hybrid heating experiments on Alcator C with 1 MW of injected power have resulted in electron and ion temperature increases of 1.2 keV and 0.8 keV, respectively, at densities of $1.4 \times 10^{14} \text{ cm}^{-3}$.

The prospects for an attractive tokamak power reactor have improved markedly since the ERAB review in 1983. Major improvements include: the possibility of stable operation at higher beta (through a variety of approaches, such as access to the second stability regime, increased elongation, low-aspect-ratio configurations, and operation at on-axis safety factors of less than one); very long plasma burns with rf current ramp-up, or full steady-state operation with non-inductive current drive; and simplified impurity control schemes (through improved poloidal divertor configurations, and new, helium-pumping materials for the divertor/limiter and/or first wall). Additional improvements have been made in identifying advanced materials (e.g., vanadium alloys) which greatly reduce long-term radioactivity, and result in longer lifetimes and higher temperature capability. New concepts such as replacing the blanket, shield and heat extraction system with a pool of molten salt exhibit excellent inherent and passive safety characteristics. Recent reactor designs, which explore a range of reactor outputs (300 MWe and larger), have shown that tokamaks can achieve mass power densities exceeding 100 kWe/tonne. Thus, a number of important ideas for improving the tokamak as a power reactor have been developed, and many of these concepts are being explored in experimental programs.

b. Alternate Fusion Concepts

Although at an earlier state of development and demonstrated plasma performance, the alternate fusion concepts are making impressive technical progress in their own right, and they also contribute to the fusion program through advances in the basic understanding of plasma confinement properties, and through the development of advanced technologies. Two examples are the stellarator and the reversed field pinch. As presently designed, the ATF stellarator experiment at Oak Ridge National Laboratory will provide a significant complement to foreign stellarator experiments, and make strong contributions to toroidal concept development. Progress in research on the reversed field pinch has been outstanding, and this concept is

technically ready to proceed with a device that has toroidal current capability in the 2 megampere range or beyond.

The Advanced Toroidal Facility (ATF) will be the world's largest stellarator facility when its construction is completed at the end of 1986. The main technical emphasis will include: (a) high-beta operation, in which beta values up to 8% may be attained by direct access to the second-stability regime, and (b) experimental studies of transport properties, particularly at low collisionality. Theoretical models, consistent with existing stellarator data, indicate that plasma temperatures of several keV at densities of $2 \times 10^{13} \text{ cm}^{-3}$ may be attained with the available heating power. Initial operation will be in the pulsed mode, but the longer-term goal is to implement the inherent steady-state capability of the device.

Since the 1983 review, experiments on ZT-40 and OHTE have advanced significantly the data base for reversed field pinches. Scaling studies on ZT-40 have yielded temperatures up to 600 eV, beta values in the range 20-30%, and values of the Lawson confinement parameter up to $n_0 \tau_E \sim 6 \times 10^{10} \text{ cm}^{-3}\text{-sec}$. These scaling studies, which have been carried out for toroidal currents up to 500 kA, suggest that the reversed field pinch has the potential to achieve ignition parameters with ohmic heating alone.

Continuous sustainment of the reversed field pinch configuration by means of self-relaxation has been experimentally demonstrated on ZT-40, with discharge durations at least ten times greater than resistive relaxation times. An improved theoretical understanding of the associated continuous regeneration of the toroidal flux has been obtained. These observations have led to the development of a new steady-state current-drive concept, applicable to the tokamak and the reversed field pinch, which requires relatively simple technology involving low-amplitude 60 Hz modulation of the plasma current.

The TMX-U tandem mirror has demonstrated thermal barrier end plugging up to central cell densities of $3 \times 10^{12} \text{ cm}^{-3}$, a factor of three below the original design value. Newly developed diagnostics, designed to measure potential internal to the plasma, have provided a large body of data that is consistent with the thermal barrier model. The TMX-U experiment has demonstrated central-cell nonambipolar ion transport consistent with theory. In addition, there is radial ion transport in the plugs of

comparable magnitude. The total radial ion transport has been reduced to a low level through the use of segmented end-wall plates, which permit adjustment of the radial potential profile.

Construction of the TARA tandem mirror has been completed, and experiments with thermal barrier end plugging have begun. The startup configuration using weak anchor plugging has established central-cell densities of $3.5 \times 10^{12} \text{ cm}^{-3}$, perpendicular ion temperatures of 500 eV, and parallel ion temperatures of 150 eV. Initial thermal barrier plugging has been measured for central cell densities of 10^{12} cm^{-3} . This versatile facility investigates magnetically symmetric geometries that may lead to a significantly improved reactor configuration.

The MFTF-B PACE project was completed in February, 1986, with successful performance tests of the vacuum, magnet, cryogenic, and computer and control systems, with all systems performing at design specifications. Budget constraints have forced a mothballing of this major new tandem mirror facility.

The production of spheromak plasmas has been demonstrated experimentally by several techniques, and non-radiation-dominated plasmas with electron temperatures exceeding 100 eV have been produced, allowing initial studies of the relevant transport properties. Magnetic helicity, the linkage of flux with flux, has been identified as an important concept for spheromaks, and the conservation of helicity for times shorter than the resistive diffusion time has been demonstrated. Systems studies have shown the spheromak to have potentially the highest value of mass power density in a fusion reactor, with considerable simplification of the technology, and a significant lowering of the reactor costs compared with other concepts.

Experimental studies of field-reversed configurations (FRCs) have shown that translating the plasma from the region of formation into another chamber does not adversely affect the confinement properties of the configuration. This enhances the prospects for reactor design simplification stemming from the freedom to separate the region of plasma formation from the region of neutron production. Field-reversed configurations have operated at beta values up to 80%, temperatures up to 200 eV, and the values of the Lawson parameter up to $n_0 \tau_E \sim 4 \times 10^{11} \text{ cm}^{-3} \cdot \text{sec}$.

c. Fusion Theory and Computations

Significant advances have been made in plasma theory and computations, which are now able to describe in detail most large-scale phenomena of confined plasmas, and which are beginning to provide valid understanding of microscopic phenomena. Accomplishments of particular note include: (i) the successful description of the nonlinear regime of resistive instabilities and the circumstances leading to disruptions in tokamaks, (ii) the detailed delineation of stability limits on beta in a tokamak for a wide variety of plasma profiles and cross sections, (iii) the accurate identification and characterization of microinstabilities and mechanisms for their stabilization in mirror configurations, and (iv) the identification of magnetic helicity (the linkage of flux with flux) as an important concept for compact toroids, leading to the invention of novel formation techniques and current-drive methods based on helicity injection.

d. Development and Technology

The technology for single-and multiple-pellet injectors for plasma fueling has made rapid technical progress. Pellet diameters up to 4 mm and injection velocities up to 1.9 km/sec have been achieved. Pellet injection experiments on TFTR and Alcator C have produced significant increases in central plasma density, peaking of the density profiles, and improved energy confinement.

In the area of rf source development for electron cyclotron heating (ECH), the program on cw gyrotrons at 60 GHz and 200 kW has been completed successfully. The research and development effort is now focused on gyrotron sources at higher frequency (140 GHz), for both pulsed (1-2 MW) and steady-state (200 kW) operation.

The Tritium Systems Test Assembly (TSTA) has operated successfully with 30 grams of tritium, and preparations are underway for 130 gram operation. There is strong participation by Japan in testing on TSTA.

Research on structural materials for fusion reactors has shown that austenitic stainless steel performs satisfactorily in a fusion neutron environment up to fluences of $10 \text{ MW} \cdot \text{years/m}^2$. In the area of plasma-interactive materials, experimental studies of sputtering and surface materials redeposited on the first wall have been initiated.

Despite project delays, the Large Coil Test Facility (LCTF) has been completed, and the six superconducting coils (three U.S. coils and three coils from Europe, Japan and Switzerland) have been installed, cooled and tested individually. Preparations for multiple-coil tests are in progress.

The fusion systems studies program has proved very cost effective in carrying out its purposes. At approximately 3% of the magnetic fusion budget, it has provided "eyes to the future" for guidance of the larger program. Its impact has been frequent, widespread and significant. The systems studies program carries out conceptual design studies in three general areas: (a) In the area of commercial reactor studies, the systems studies program has evaluated several reactor concepts for tokamaks and the alternate approaches, given guidance to the respective research programs, and generated innovative solutions to perceived reactor shortcomings; (b) In the area of next-generation devices, the systems studies program has evaluated several next-step options covering a wide spectrum of performance and costs, ranging from the compact ignition tokamak (CIT), to the engineering test reactor (ETR), to the international tokamak reactor studies (INTOR) project; (c) For both commercial reactors and next-generation devices, the systems studies program has also investigated several critical technical areas that involve the interaction of physics and technology, e.g., blanket comparisons and impurity control.